PUMP AND FAN CONTROL CONCEPTS IN A COOLING SYSTEM

Related Application

This Patent Application claims priority under 35 U.S.C. 119 (e) of the co-pending U.S. Provisional Patent Application, Serial No. 60/489,730 filed July 23, 2003, and entitled "PUMP AND FAN CONTROL APPARATUS AND METHOD IN CLOSED FLUID LOOP ". The Provisional Patent Application, Serial 60/489,730 filed July 23, 2003, and entitled "PUMP AND FAN CONTROL APPARATUS AND METHOD IN CLOSED FLUID LOOP" is also hereby incorporated by reference.

Field of the Invention

This invention relates generally to the field of thermal management systems. More specifically, this invention relates to cooling heat-generating devices by using various temperature sensors, control schemes and thermal models, through the control of operating conditions of a pump and a fan in a cooling system.

Background of the Invention

A variety of applications require cooling of devices that have very high heat fluxes, such as in the range of 50-1000 W/cm^2. These devices include integrated electronic circuits in microprocessors, laser diodes, and power semiconductor devices for control electronics.

In conventional electronic systems, such as computers, heat generated by one or more of these heat-generating devices is transferred to its surroundings through the use of a heat sink and one or more fans. Conventional heat sinks are passive except for the use of the fans, which can be controlled based on a signal from a temperature sensor within the computer or on the heat-generating device. The fans draw cool air into the heat sink and push warm air out. There may also be fans mounted directly on the heat sink. In some circumstances, the fan speed is

controlled such that it increases when the device gets warmer and decreases when the device gets cooler. The goals of the heat sink and fan assembly are generally to keep the device below an acceptable maximum temperature.

What is needed is an improved cooling system that regulates both pump and fan speed in a concerted manner to maintain a heat-generating device within its allowed temperature range while conserving power and reducing system noise and transients thereof.

Brief Summary of the Invention

According to a first aspect of the present invention, an apparatus for controlling a fluid flow rate of at least one pump and an air flow rate of at least one fan, in a cooling system for cooling at least one device is disclosed. The apparatus comprises a means for sensing a temperature value of the device. The means for sensing the temperature value can be at least one temperature sensor coupled to measure a temperature value of the device or devices. Alternatively, if the device is an electronic circuit, such as a microprocessor, the means for sensing the temperature value can be an electric current or electric power sensor from which temperature of the device is inferred. A controller is coupled to receive the temperature value and to selectively control the fluid flow rate, the air flow rate, or both based on the temperature value. The fluid system can be a closed loop system.

The apparatus can further include a heat exchanger thermally coupled to the device where at least a portion of the heat exchanger is filled with a thermal capacitance medium for maintaining the temperature value of the device below a maximum allowable temperature during thermal transients. The medium is preferably laterally distributed in the heat exchanger. Either the pump or the fan or both can be controlled such that the temperature value of the device is maintained below a maximum allowable temperature. Alternatively, one of the fan and pump can be maintained at a constant maximum speed and the other of the fan and pump controlled such that the temperature value of the device is maintained below a maximum allowable temperature such that acoustic transients are reduced. The pumps can be controlled

independently of the fans. Alternatively, the pumps can be controlled cooperatively with the fans in a manner that optimizes one or more of several performance metrics.

The apparatus can further include at least one current sensor coupled to one or more devices, to provide information which is representative of the current delivered to the devices and indicative of the total electric power consumed by each of the devices. The total electric power consumed by each device is proportional to the steady-state operating temperature of that device. The controller is coupled to receive the information provided by the current sensors. The controller can adjust a current supplied to the pumps and the fans in response to the measured current values of each device. The controller can also adjust a voltage supplied to the pumps and the fans in response to the measured temperature values of each device. The system can have one or more pumps, fans, devices, heat exchangers, heat rejectors, controllers, and sensors.

The apparatus can also include a valve or valves for regulating the fluid flow rate. Each valve is selectively opened and closed to a variable state in response to one of the measured quantities, such as the temperature value of a device.

Power consumption of the cooling system can be reduced to a minimal level responsive to changes in demand for delivering power to each pump and fan. Time variations in noise level of each fan and pump can be minimized according to a predetermined criteria. A sum of the noise level of each fan and pump can be minimized. The temperature of each device can be maintained between a minimum temperature level and a maximum temperature level, while assuring that the power consumption of the cooling system is reduced to a minimum level.

In one embodiment, the controller can include a control algorithm based on a thermal time constant, wherein the thermal time constant is a product of a thermal resistance value and a thermal capacitance value. The thermal time constant can be applied to develop optimal control schemes for the pumps and the fans, in response to power consumed from the device or devices. The optimal control schemes can adjust the fluid flow rate of one or more pumps, the air flow rate of one or more fans, or both. For example, the optimal control schemes can include increase of fluid flow rate of the pump, with no increase of air flow rate of the fan. Alternatively, the

optimal control schemes can include increase of fluid flow rate of the pump, with a gradual increase of air flow rate of the fan, thus reducing acoustic transients. Alternatively, the optimal control scheme can include decrease of fluid flow rate of the pump, with no change of air flow rate of the fan.

According to an alternative aspect of the present invention, an apparatus for controlling a fluid flow rate of at least one pump in a cooling system for cooling at least one device is disclosed. The apparatus comprises at least one temperature sensor for measuring a temperature of the device, the fluid, or both. Alternatively, the power consumed by the device can be measured and used to estimate the temperature of the device. The apparatus also includes at least one controller for varying the fluid flow rate of the pump based on the temperature of the device. The controller preferably drives each pump at roughly a constant low fluid flow rate when the measured device temperature is below a predetermined temperature value and at roughly a constant high fluid flow rate when the measured fluid temperature is above the predetermined temperature value. Further, the controller preferably drives each pump at a minimum pump voltage or pump current when the measured device temperature is below a predetermined minimum temperature value and at a maximum pump voltage or pump current when the measured device temperature is above a predetermined maximum temperature value. The controller can drive each pump between a pump minimum flow rate and a pump maximum flow rate in response to the measured device temperature.

The system can further include at least one fan, wherein the one or more pumps are controlled in response to the measured device temperature while the fan remains at a roughly constant operational state, thereby minimizing time variations of noise level generated by the fans and the pumps. The time variations of noise level of the pumps can be minimized according to predetermined criteria. The noise level generated by each pump can be maintained at a minimum noise level.

In another embodiment of the present invention, a method of controlling a fluid flow rate of at least one pump and an air flow rate of at least one fan, in a cooling system for cooling at

least one device is disclosed. The method comprises the steps of: providing at least one temperature sensor coupled to measure a temperature value of each device; receiving the temperature value from each temperature sensor; and providing a controller to selectively control the fluid flow rate and the air flow rate, based on each temperature value. The method can further include the step of filling at least a portion of a heat exchanger with a thermal capacitance medium for maintaining the temperature value of the device below a maximum allowable temperature during thermal transients, wherein the heat exchanger is thermally coupled to the device.

In another embodiment of the present invention, an apparatus for controlling a fluid flow rate of at least one pump and an air flow rate of at least one fan, in a cooling system for cooling at least one device, is disclosed. The apparatus comprises at least one circuit for measuring a current consumed by the device and for forming a signal representative thereof; and a controller coupled to receive the signal and to selectively control the fluid flow rate and the air flow rate, in response thereto.

Brief Description of the Several Views of the Drawings

Figure 1 illustrates a cooling system in accordance with an embodiment of the present invention.

Figure 2 illustrates a thermal circuit model for a cooling system in accordance with the present invention.

Figure 3 is a schematic flowchart illustrating steps of an alternative method of the present invention.

Figure 4A is a schematic flowchart illustrating steps of an alternative method of the present invention.

Figure 4B is a schematic flowchart illustrating steps of an alternative method of the present invention.

Figure 5 illustrates a schematic diagram of an alternative system of the present invention.

Figure 6 illustrates the temperature and power consumption of the device of Figure 1 as a function of time under both steady state conditions prior to a time T and during a surge in power consumption of the device at time T.

Figure 7 illustrates the effect of introducing thermal capacitance to the system of Figure 1 so that the temperature of the device of Figure 1 is maintained below a maximum allowable temperature during a surge in power consumption of the device at time T.

Detailed Description of the Invention

Reference will now be made in detail to the preferred and alternative embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the invention will be described in conjunction with the preferred embodiments, it will be understood that it is not intended to limit the invention to these embodiments. On the contrary, the invention is intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope of the invention as defined by the appended claims. Furthermore, in the following detailed description of the present invention, numerous specific details are set forth in order to provide a thorough understanding of the present invention. However, it should be noted that the present invention may be practiced without these specific details. In other instances, well known methods, procedures and components have not been described in detail as not to unnecessarily obscure aspects of the present invention.

Referring now to the drawings and particularly to Figure 1, there is shown one embodiment of a cooling system 100, which can include a hermetically sealed loop, that can be used in the apparatus and method of the present invention. The system 100 comprises a heat exchanger 120, in which a fluid absorbs heat from a heat-generating device 125, a heat rejector 130, which transfers heat from the liquid to a surrounding ambient environment, and a pump 110, which forces the fluid to flow through the heat exchanger 120 and then through the heat rejector 130. Though the heat exchanger 120 includes microchannels 121, it will be appreciated by those of ordinary skill in the art that other types of heat exchangers can be used under the teachings of

the present invention including those without microchannels. For example, as an alternative the heat-generating device 125 can be designed with internal flow regions or microchannels built into the heat-generating device 125. The heat-generating device 125, of which the system 100 can include one of many types of heat sources including but not limited to an integrated electronic circuit in microprocessors, laser diodes, and power semiconductor devices for control electronics. The fluid travels through the system 100 via a fluid transport line 105.

The system 100 circulates either the fluid without phase change or with phase change, such as boiling, and then condensing at the heat rejector 130. The heat rejector 130 can include a plurality of fins 135 for further assisting in conducting heat away from the system 100. The heat rejector 130 can be coupled to a fan 140 via the fins 135, and is therefore positioned in an airflow path of the fan 140. However, the fan can be located at any location in the system 100.

The pump 110 and the fan 140 are responsive to a controller 150. The controller 150 receives data input through electrical signal paths 155, 165 and 175, to numerous sensors, for example temperature sensor 75, positioned to measure a heat operating level of the heat-generating device 125 and the temperature within the heat exchanger 120. The heat operating level can be a die temperature during operation of the system 100. Temperature sensors (not shown) can also be located within the heat rejector 130, the fins 135, the pump 110, and anywhere along the fluid transport line 105 for the fluid at any point in the system 100. The temperature sensor (not shown) can also be embedded in the device 125 and a representative signal can be provided by the device 125. Additional electrical signal paths (not shown) can be coupled to the heat rejector 130, the fins 135, anywhere along the fluid transport line 105, and to any location where there is a sensor. The sensors generate signals that represent the temperature sensed and transmit those signals over the electrical signal paths 155, 165 and 175 to the controller 150. Also, the system 100 can include current sensors (not shown) and pressure sensors (not shown) for one or more heat-generating devices in the system 100. The current sensors (not shown) and the pressure sensors (not shown) can generate an output signal proportional to temperature. In addition to temperature sensors, current sensors and pressure

sensors, ambient temperature sensors (not shown) to measure temperature values of ambient air around the heat-generating device 125, and flow rate sensors (not shown) with corresponding flow valves (not shown) can be added. It should also be understood, in accordance with the present invention, that the controller 150 can be configured to simultaneously respond to multiple sensors, or to modify an operating state of various components such as the pump 110 and the fan 140. The present invention further discloses a system having one or more pumps, fans, heat-generating devices, heat exchangers, heat rejectors, controllers, and sensors.

The controller 150 coordinates the various signals received and controls a flow rate of the pump 110 and an airflow of the fan 140, via wires 165 and 155, respectively, in response thereto. For example, the controller 150 can actuate the pump 110 to increase an amount of flow if the temperature of the heat-generating device 125 is above a specified temperature, or it can decrease the amount of heat being removed if the temperature of the heat-generating device 125 is below the specified temperature. Alternatively, the controller 150 can stop the pumping of the fluid altogether when the temperature of the heat-generating device 125 falls below the specified temperature. As mentioned above, the controller 150 can also regulate the airflow of the fan 140. For example, the controller 150 can actuate the fan 140 to increase airflow if the temperature of the heat-generating device 125 is above the specified temperature, or it can decrease the airflow of the fan 140 if the temperature of the heat-generating device 125 is below the specified temperature. Alternatively, the controller 150 can stop the airflow of the fan 140 altogether when the temperature of the heat-generating device reaches the specified temperature. It should also be understood, in accordance with the present invention, that the controller 150 can be configured to control both the pump 110 and the fan 140 cooperatively or independently to achieve and maintain proper regulation of the system 100, and also to reduce power consumption of the system 100 to a minimal level responsive to changes in demand for delivering power to the pump 110 and the fan 140. Alternatively, the controller 150 can be configured to reduce an acoustic noise level of the system 100 to a minimal level responsive to changes in demand for delivering power to the pump 110 and the fan 140.

An important feature of the present invention is that a temperature value of the heat-generating device 125 can be maintained between a minimum temperature level and a maximum temperature level, such that the power consumption of the system 100 or the acoustic noise level of the system 100 or both is reduced to a minimum level. Further, the controller 150 can be coupled to a control valve 112 of the system 110. Thus, the controller 150 can open or close the control valve 112 to a variable opening position in response to the temperature value. The controller 150 can also control the pump 110 and the fan 140 in response to the temperature of the heat-generating device 125 and/or the fluid at any location in the system 100.

In prior art cooling systems utilizing conventional heat sinks, when fan voltage is reduced to reduce noise, the heat sink temperature immediately increases. At the same time, the temperature of the heat-generating device will increase accordingly. In the present invention, the system 100 can reduce noise generated by the fan 140 and/or the pump 110 while maintaining adequate cooling of the heat-generating device 125. The pump 110 and the fan 140 can have relationships between speed and noise. Further, time variations in noise level of at least one of the fan 140 and the pump 110 can be minimized according to predetermined criteria. If the pump 110 is an electrokinetic pump, for example, it will be silent or nearly silent during operation. Therefore, the system 100 can minimize noise by operating the pump 110 at a maximum flow rate, and operating the fan 140 at a minimum rate which provides adequate cooling performance. Alternatively, the pump 110 and the fan 140 can have relationships between noise and power. The system can be optimized to provide adequate cooling power while minimizing power consumption of the fan 140 and the pump 110. In addition, the system 100 can control "operational states" for the fan 140 and the pump 110, such as voltage, current, or an operational curve relating pressure to flow rate for the pump 110 and/or the fan 140, to maximize reliability, or to minimize other desirable characteristics, such as changes in the speed of the fan 140, variations in the airflow of the fan 140 past other components or parts of the system 100, EMI (electromagnetic interference) generation by the fan, accumulation of dust, and so forth. As an example, the controller 150 can gather data relating fan speed to power consumption and airflow

of the fan 140. With the heat exchanger 120 and the heat rejector 130 as components of the system 100, it is possible to characterize thermal performance of the system 100 as a function of the "operational states" of the fan 140 and the pump 110.

The system 100 can be characterized in general as single-input-multiple-output (a single thermal input signal used to control one or more pumps and one or more fans), or multiple-input-multiple-output (more than one input signal used to control one or more pumps or one or more fans). The present invention discloses the use of single-input-multiple-out or multiple-input-multiple-output control systems for all electronic cooling systems that include at least one pump and at least one fan.

Another inventive feature of the present invention is that the controller 150 can use a cost function for optimization of various components, such as the heat exchanger 120, to minimize operation costs while maintaining adequate cooling conditions within the system 100. Optimization can be achieved by determining the power consumption of the system at minimal levels, the time variations at a minimal noise level, the temperature values maintained between the minimum and maximum temperature levels, and the noise level generated and maintained at the minimum noise level.

Figure 2 is a thermal circuit model 200 for a cooling system, which is analogous to an electrical circuit. The thermal circuit model 200 divides the system into two separate groups of thermal resistors and thermal capacitors between three temperature nodes, namely, heat-generating device temperature 215, the average fluid temperature 235, and ambient air temperature 245. A heat exchanger thermal resistance 220 depends on a pump flow rate geometry, material and design of the heat exchanger. A heat rejector thermal resistance 240 depends on the pump flow rate and a fan flow rate. The thermal resistance is described by a rise in temperature for each unit in thermal resistance passing through the material. A heat exchanger thermal capacitance 210 and a heat rejector thermal capacitance 230 describe an amount of energy taken in by those components for each degree of temperature rise. A current source 255 models the thermal power output of the heat-generating device.

According to the thermal circuit model 200, the ambient air temperature 245, modeled as an electrical circuit node, is coupled to a first terminal of the heat rejector thermal resistance 240, modeled as a electrical resistor, and also to ground. A second terminal of the heat rejector thermal resistance 240 is coupled to the average fluid temperature 235, modeled as an electrical circuit node, and also to a first terminal of the heat rejector thermal capacitance 230, which is modeled as an electrical capacitor. A second terminal of the heat rejector thermal capacitance 230 is coupled to ground. The fluid temperature 235 is also coupled to a first terminal of the heat exchanger thermal resistance 220, modeled as an electrical resistor. A second terminal of the heat rejector thermal resistance 240 is coupled to the heat-generating device temperature 215, modeled as an electrical circuit node, and also to a first terminal of the heat exchanger thermal capacitance 210, which is modeled as an electrical capacitor. The heat-generating device temperature is also coupled to the thermal output of the heat-generating device which is modeled as an electrical current source 255.

In one embodiment of the present invention, a portion of the heat exchanger 120 (Figure 1) can be filled with a thermal capacitance medium for maintaining the temperature value of the heat-generating device 125 (Figure 1) below a maximum allowable temperature during a thermal transient or increase in power output. The medium can consist of high specific heat materials and is preferably laterally distributed in the heat exchanger 120 (Figure 1).

A thermal resistance represents a ratio of a temperature difference between, for example, the heat-generating device 125 (Figure 1) and the fluid in the heat exchanger 120 (Figure 1) divided by heat power removed from the heat-generating device 125 (Figure 1). This parameter has units of degrees/watt, and small ratio values represent better system performance than large ratio values. As an example, if the ambient air temperature is 40 degrees Celsius and the heat-generating device 125 (Figure 1) cannot operate above 100 degrees Celsius, and the power consumption is 60 Watts, the thermal resistance must be lower than 1 degrees/Watt. A higher thermal resistance would lead to a higher operating temperature for the heat-generating device 125 (Figure 1). Total resistance between the heat-generating device 125 (Figure 1) and the

ambient air is the sum of the heat-generating device-fluid temperature resistor 220 and the fluid-ambient resistor 240. For a control scheme where both fan speed and pump flow rate are controllable, it is useful and approximately correct to break the system resistance into the two resistors 220 and 240, as shown in Figure 2, and to associate the two resistors 220 and 240 with the capacitors 210 and 230 as indicated in Figure 2.

The thermal resistance between the heat-generating device 125 (Figure 1) and the fluid decreases with increasing values of the flow rate of the pump 110 (Figure 1). For a given value of total thermal resistance, there can be many combinations of pump and fan speed that provide an adequate system performance. In general, it is possible to reduce the speed of the fan 140 (Figure 1) and increase the speed of the pump 110 (Figure 1) and still maintain adequate system performance. This would result in a decrease in the heat exchanger thermal resistance 220 (R_{hx}) and an increase in the heat rejector thermal resistance 240 ($R_{rejector}$). Since the pump and fan can be independently controlled, it is possible to arrange for a fixed total thermal resistance while changing the pump and fan operation such that: $R_{hx} + R_{rejector}$ = constant). This would allow optimization of some other parameter , such as total power or total noise, while maintaining desired cooling system performance.

The controller 150 (Figure 1) can include a control algorithm based on a thermal time constant, which is the product of thermal resistance and thermal capacitance. The thermal capacitance of the heat exchange and the heat rejector can be adjusted by changing the mass of their respective structures, by changing their materials or by adding a layer of material with different thermal properties.

As an example, consider the case that the heat-generating device is a microprocessor. The amount of electric power consumed by the device varies substantially as the tasks performed by the microprocessor change. Typical microprocessors have a maximum allowable temperature (MAT). Ideally, the microprocessor is allowed to operate at a relatively high temperature, just below the MAT, so that the electric power consumed by and also the acoustic noise generated by the cooling are both minimized.

As the amount of electric power changes the temperature of the device changes nearly immediately in the absence of the present invention. Figure 6 shows a microprocessor initially operating in steady state, with a temperature lower than the MAT. At a time T, the electric power (in Watts) consumed by the microprocessor increases. The temperature of the device rises very quickly. With prior art systems, the temperature of the microprocessor would need to operate much lower than the MAT or else increases in power consumption would allow the temperature to exceed the MAT. This is especially true because prior art systems could not react quickly to changes in device temperature

The present invention contemplates appropriately selecting the thermal capacitance to accommodate transient power signals. By adjusting the thermal capacitance of the system of the present invention, the time for the device to increase in temperature increases is slowed. In Figure 7, the microprocessor again increases its electric power consumption at time T. However, because the thermal capacitance of the system is increased, the temperature of the microprocessor increases relatively slowly allowing the system ample time to compensate for the increased thermal power output of the microprocessor by appropriately adjusting the fluid flow rate of the pump or the air flow rate of the fan or both as discussed herein. This allows the designer to select a thermal capacitance relative to the desired thermal guardband to control the amount of electric power consumed by the one or more pumps and the one or more fans in the system. As the thermal capacitance is decreased, the thermal guardband is correspondingly increased such that more electric power is consumed by the cooling system of the present invention. Likewise, as the thermal capacitance is increased, the thermal guardband is correspondingly decreased and less electric power is consumed by the cooling system.

Control schemes can be developed and based on a thermal time constant. The thermal time constant can be applied to develop optimal control schemes for the pump 110 (Figure 1) and the fan 140 (Figure 1), in response to temporal power signal consumed by the heat-generating device 125 (Figure 1). For example, upon knowing the thermal time constant of the heat exchanger (Figure 1), and a range of power surges of the heat generating device 125 (Figure 1),

optimal control schemes can be designed to operate the fan 140 (Figure 1) and the pump 110 (Figure 1) so that the temperature of the heat generating device 125 (Figure 1) is maintained at a "margin" below a maximum temperature at normal operating conditions. During a power surge of the heat generating device 125 (Figure 1), the pump 110 (Figure 1) and the fan 140 (Figure 1) will react immediately, but the device 125 (Figure 1) temperature will not exceed beyond the maximum temperature, therefore not allowing the heat generating device 125 (Figure 1) to throttle back. This feature of the present invention allows the heat generating device 125 (Figure 1) to operate at full performance regardless of any power surge while also reducing transients in acoustics.

The optimal control schemes can also include an increase of fluid flow rate of the pump 110 (Figure 1), with no increase of air flow rate of the fan 140 (Figure 1). Alternatively, the optimal control schemes can include an increase of the air flow rate of the fan 140 (Figure 1), with no increase in the fluid flow rate of the pump 110 (Figure 1). The fan speed can be increased slowly in order to reduce any acoustic transients. The optimal control schemes can include use of empirical data for developing the optimal control schemes. The empirical data can include temperature measurements of each heat-generating device 125 (Figure 1), the fluid in the heat rejector 130 (Figure 1), and the fluid in the heat exchanger 120 (Figure 1), as a function of either pump flow rate of the pump 110 (Figure 1) or air flow rate of the fan 140 (Figure 1), or both.

The use of a current sensor in the system provides some unique advantages. The current sensor directly detects the power input to the heat generating device, and is therefore a predictor of temperature changes. The temperature sensors have delayed responses because of the thermal time constants. Therefore a control system based on a current sensor can cause changes in pump and fan voltages that provide faster response to transients and more accurate control. In particular, an abrupt rise in current can be handled by producing an abrupt rise in pump flow rate, since the pump has a faster cooling response than the fan.

In another embodiment of the present invention, as shown in Figure 3, a method of

controlling a fluid flow rate of at least one pump and an air flow rate of at least one fan, in a cooling system for cooling at least one device, is disclosed. In the step 300, at least one sensor is provided, wherein the sensors can be temperature sensors, current sensors, or pressure sensors. Each sensor is coupled to measure a temperature value of each device; In the step 310, at least one temperature value from the at least one sensor is received. In the step 320, the fluid flow rate and the airflow rate are selectively controlled based on the temperature value .

In another embodiment of the present invention, as shown in Figure 4A, a method of controlling a fluid flow rate of at least one pump in a cooling system for cooling at least one device is disclosed. In the step 400, a temperature of the device is measured. In the step 410, the fluid flow rate of the at least one pump is varied based upon the device temperature.

In another embodiment of the present invention, as shown in Figure 4B, a method of controlling an air flow rate of at least one fan in a cooling system for cooling at least one device is disclosed. In the step 450, a temperature of the device in the system is measured. In the step 460, the air flow rate of the at least one fan is varied based upon the device temperature.

As mentioned, the present invention further discloses a system having one or more pumps, fans, heat-generating devices, heat exchangers, heat rejectors, controllers, and sensors. For example, as shown in Figure 5, a cooling system can include two pumps, two heat exchangers, one heat rejector and one fan, or other combinations.

The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of the principles of construction and operation of the invention. As such, references herein to specific embodiments and details thereof are not intended to limit the scope of the claims appended hereto. It will be apparent to those skilled in the art that modifications can be made to the embodiments chosen for illustration without departing from the spirit and scope of the invention.